Adaptive Urban Dispersion Integrated Model (AUDIM)

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Project Team

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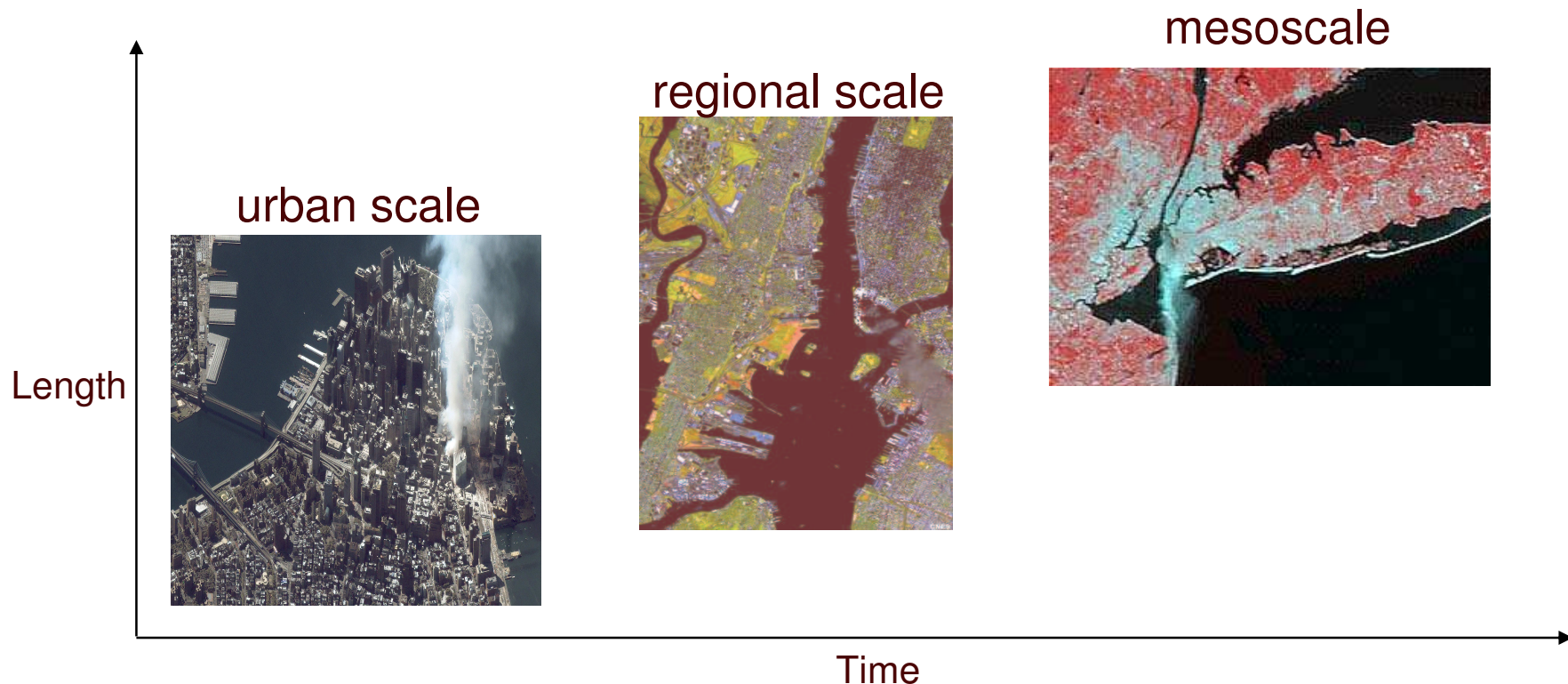*Dept. of Computer Science*
Courant Institute, NYU

Goal: Efficient, flexible, and accurate operational urban dispersion capability

urban scale, regional scale, mesoscale — Length vs Time

- **Current CFD urban dispersion models are research and planning rather than operational tools**
- **Operational urban plume dispersion tool must be fast, flexible and accurate**

Priorities for improving dispersion modeling addressed in recent NRC report

NRC of the National Academies report "Tracking and Predicting the Atmospheric Dispersion of Hazardous Material Releases – Implications for Homeland Security"
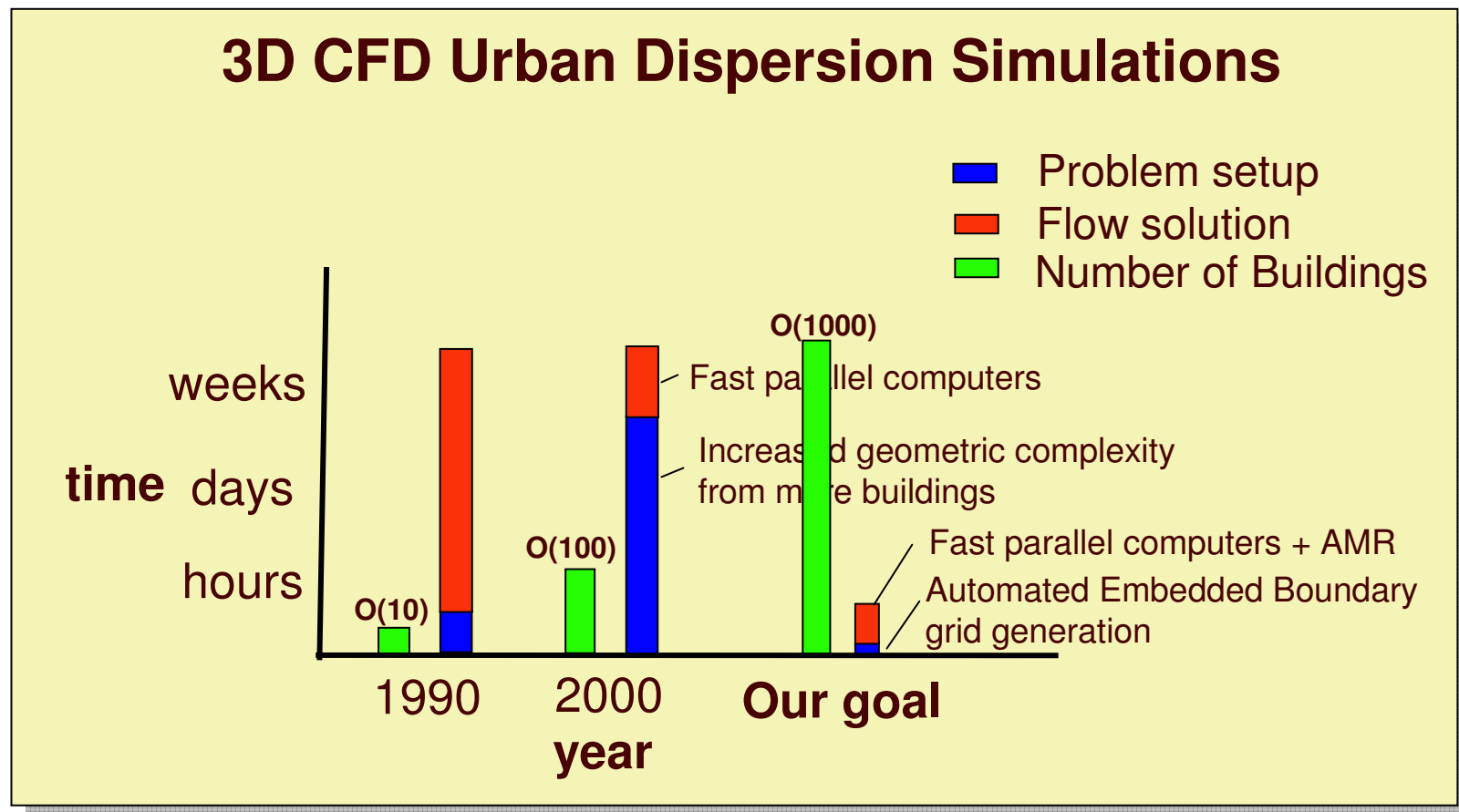
"New dispersion modeling constructs need to be further explored and possibly adapted for operational use in urban setting. This includes advanced short execution models, slower but more **accurate computational fluid dynamics** and **large-eddy simulation** models and models with **adaptive grids**." (page 5.)

"**…** no one system had all the features that the committee deemed critical:
- accommodation of **urban and complex topography**
- accurate though slower models for the **preparedness and recovery** phase"

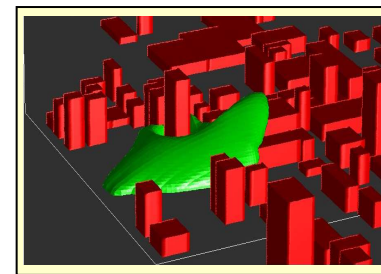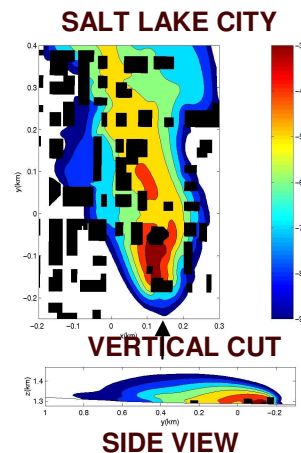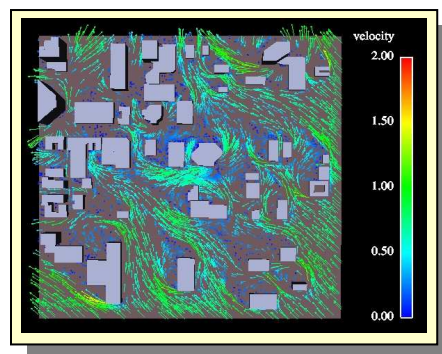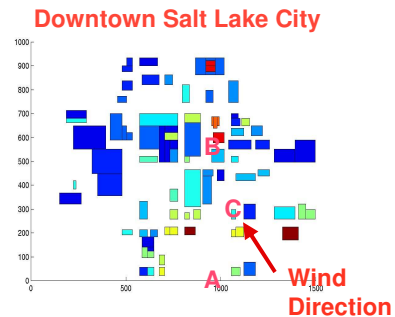# Our objective is to automate and speed up CFD dispersion prediction capability

3D CFD Urban Dispersion Simulations

Legend:
- Problem setup (blue)
- Flow solution (red)
- Number of Buildings (green)

O(10) — 1990

O(100) — 2000

O(1000) — Our goal

- Fast parallel computers
- Increased geometric complexity from more buildings
- Fast parallel computers + AMR
- Automated Embedded Boundary grid generation
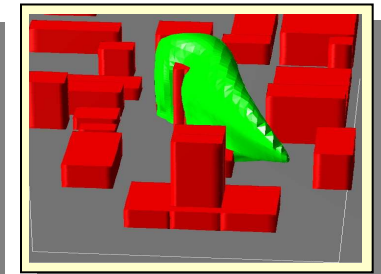
Axes: time (weeks, days, hours) vs year

FEM3MP CFD Model

- **FEM3MP is the primary urban dispersion modeling code used in the atmospheric sciences division in NARAC**

- **Validated from experiments**
  - **Joint urban 2003 in Oklahoma City**
  - **Urban 2000 in Salt Lake City**
  - **Windtunnel experiments**

Downtown Salt Lake City

Wind Direction

SALT LAKE CITY

velocity
2.00
1.50
1.00
0.50
0.00

VERTICAL CUT

SIDE VIEW

**Release south of downtown (A)**

Release in downtown area (B)

# Utilize Complex Geometry Embedded Boundary Cartesian Methods for Buildings

- **Constructing body-fitted logically rectangular grids is tedious and expensive.**

- **Embedded boundary grids constructed automatically in SAMRAI**

  – **Built from polygons or from surface triangulation using CUBES**

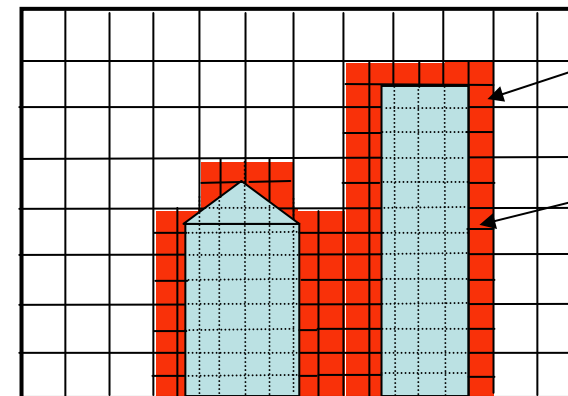 – **Refinement enhances accuracy of boundary representation**
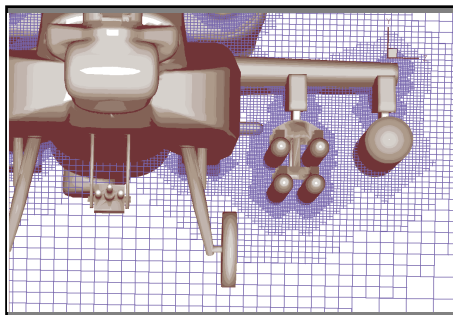
Example embedded boundary mesh constructed with CUBES

M. Berger, Courant Inst./NASA Ames
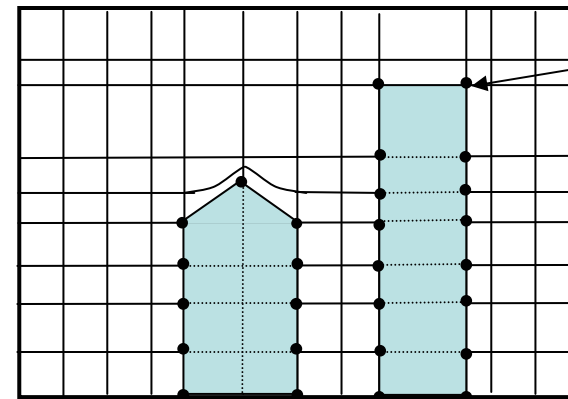
Gridlines follow building boundaries

Body-fitted grid

Cut cells

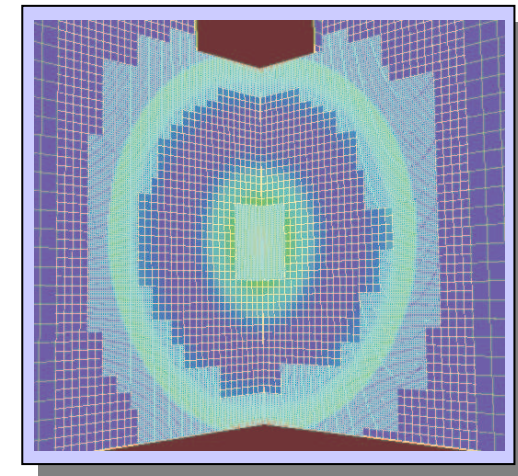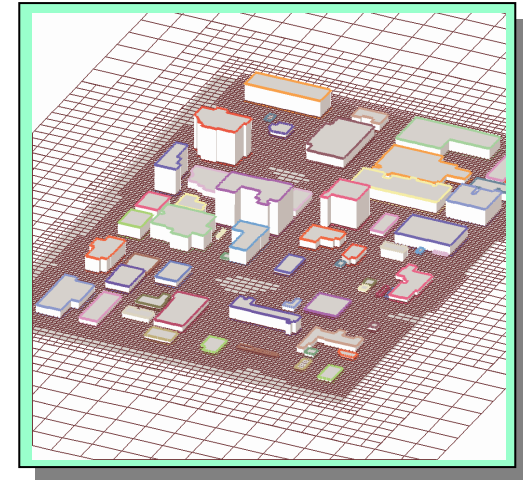Mesh refinement

Embedded Boundary Grid

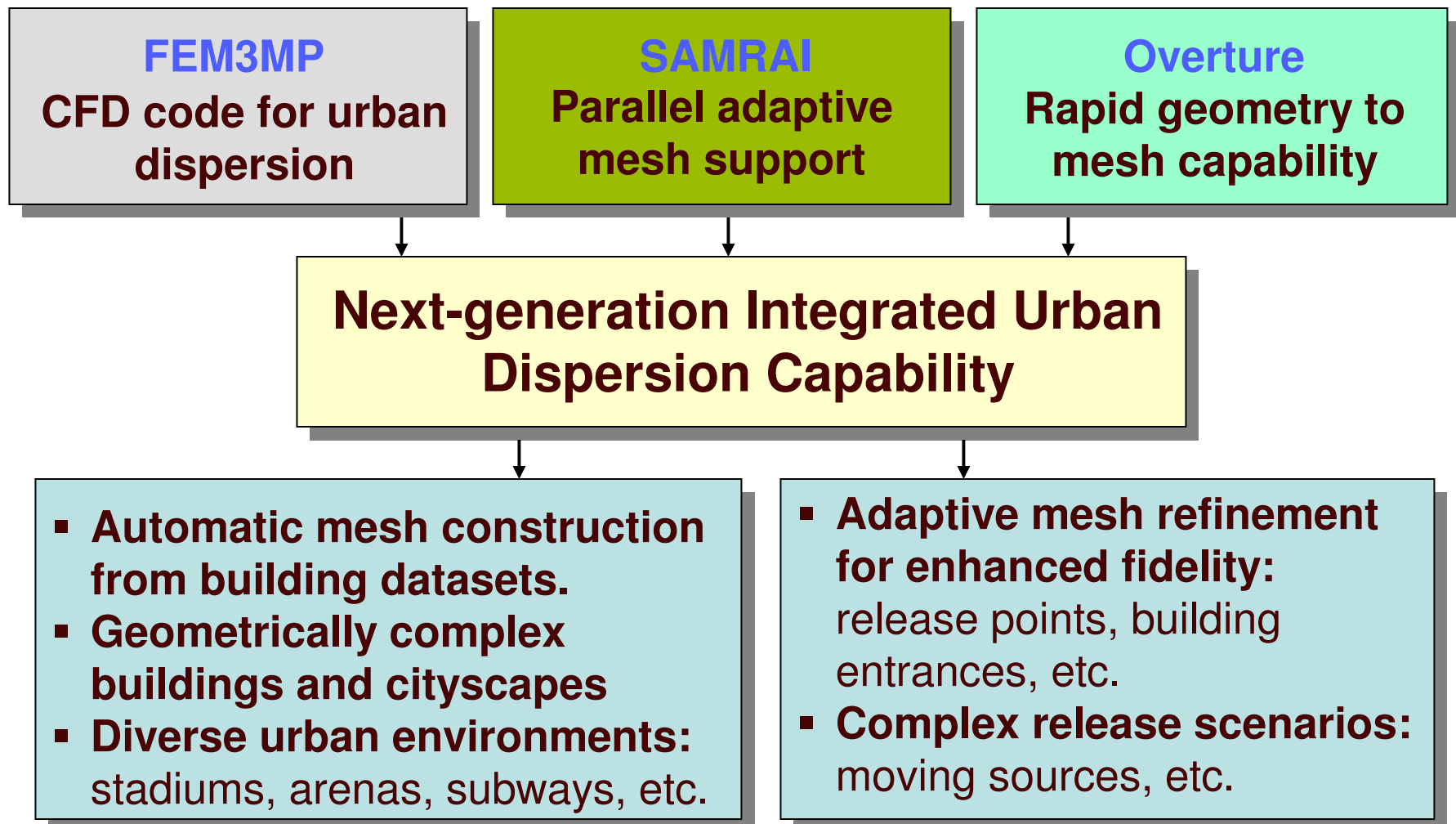# Utilize advanced meshing tools developed at LLNL

- **Overture project has tools for rapid geometry-to-mesh (Rapsodi)**
  - Rapid construction of surface grids from CAD data
  - Developed to handle complex geometries

- **SAMRAI library supports parallel AMR applications**
  - Adaptive mesh refinement (AMR) automatically enhances simulation resolution where needed.
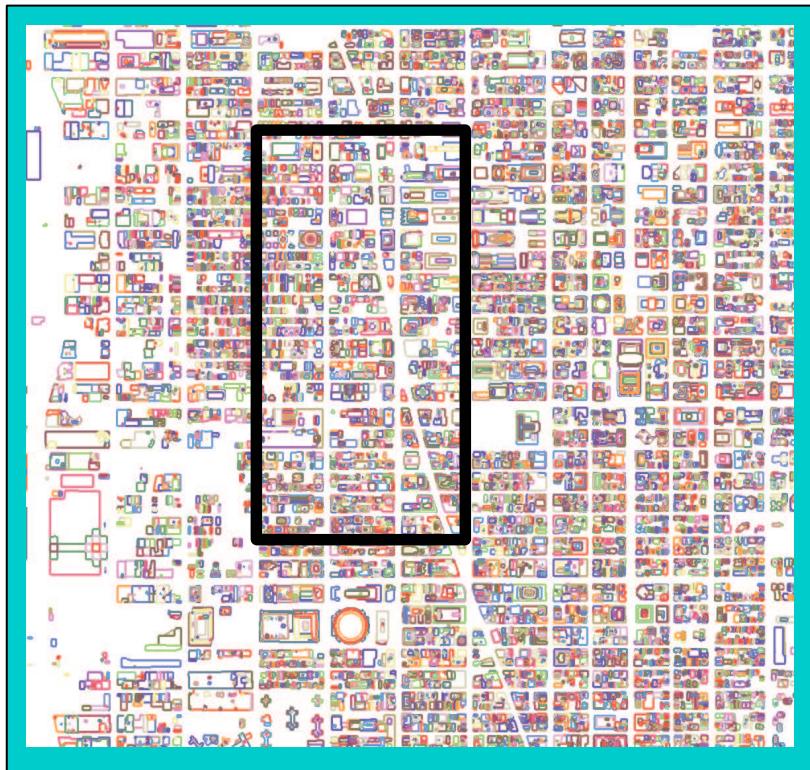 - Runs on large parallel computer systems

Couple advanced technologies to develop enhanced operational tool

FEM3MP	SAMRAI	Overture
CFD code for urban dispersion	**Parallel adaptive mesh support**	**Rapid geometry to mesh capability**

Next-generation Integrated Urban Dispersion Capability

- **Automatic mesh construction from building datasets.**
- **Geometrically complex buildings and cityscapes**
- **Diverse urban environments:** stadiums, arenas, subways, etc.

- **Adaptive mesh refinement for enhanced fidelity:** release points, building entrances, etc.
- **Complex release scenarios:** moving sources, etc.

Metro/Eleven : Interactive tools for modifying geometry
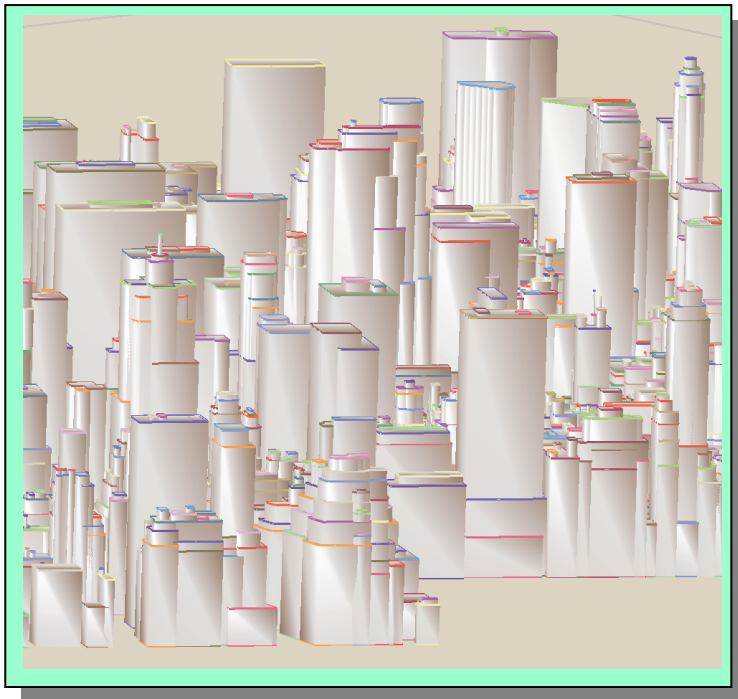

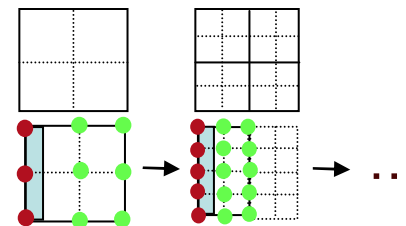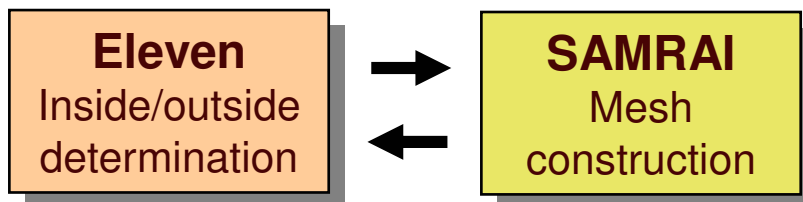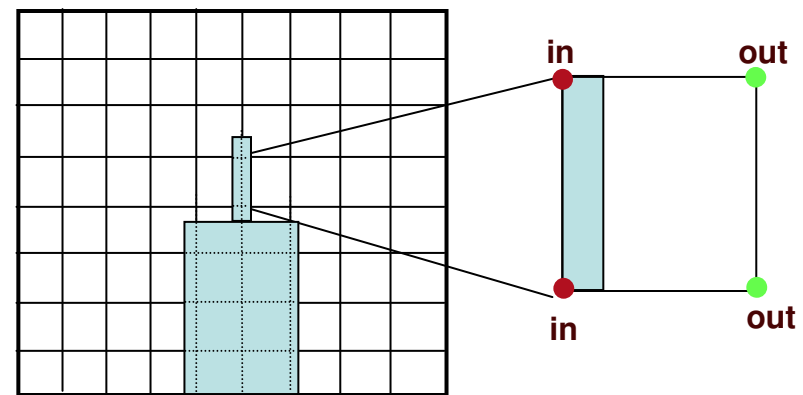Metro is built upon the ELEVEN geometry library

Modify/Add/Delete buildings
Clip out regions of interest
XML geometry database
Perl-scriptable text interface

SAMRAI/Eleven links enable modeling of complex cityscapes

- **Generating triangulated surface difficult or impossible**

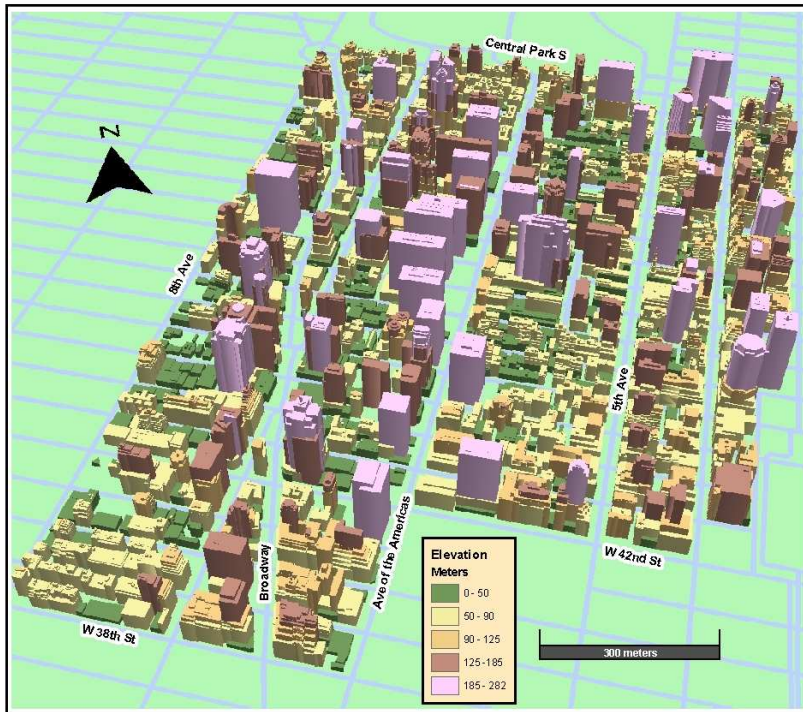- **Inside/outside determination using Polygons**

in   out

in   out

Enhanced accuracy through refinement

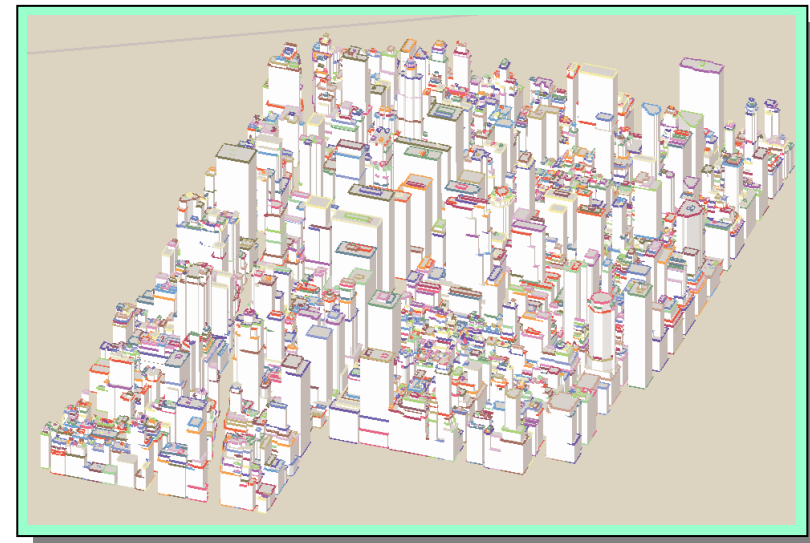| **Eleven** Inside/outside determination | → ← | **SAMRAI** Mesh construction |

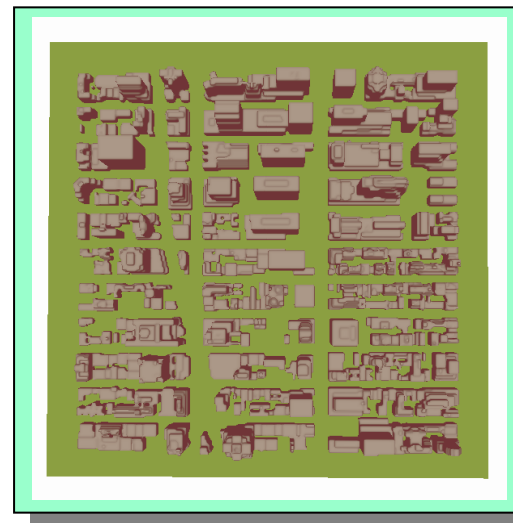# Tools utilized to mesh complex cityscapes

Midtown Manhattan

Times Square

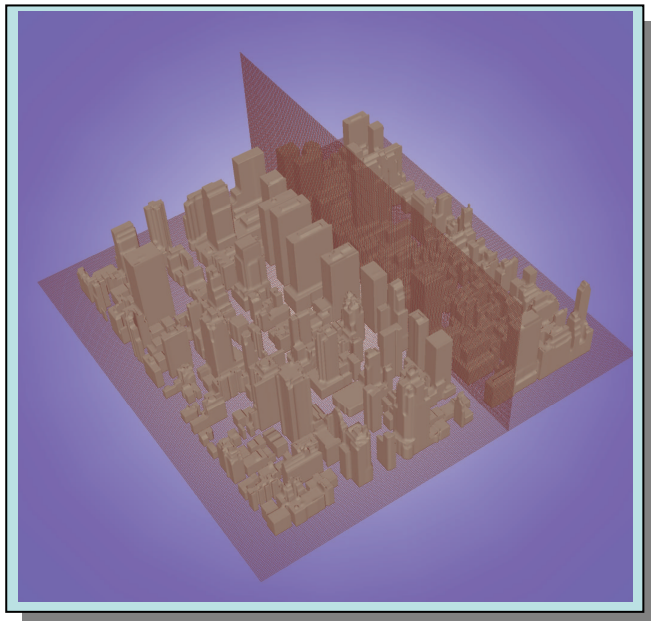**Polygonal geometry representation by metro (3600+ polygons)**

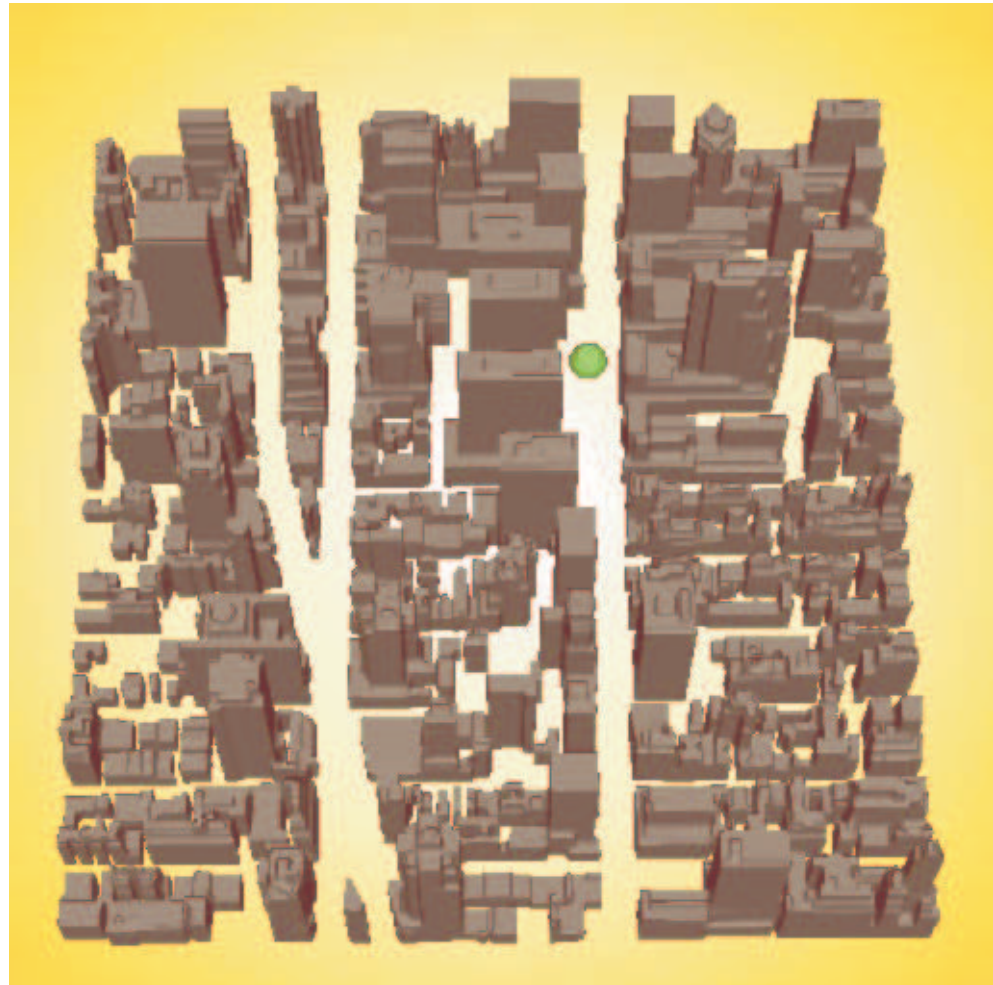# First set of delivered tools are being used for Manhattan studies

Manhattan simulations

- DHS-funded Urban Dispersion Project (UDP)

- Meshing tools used for CFD simulations
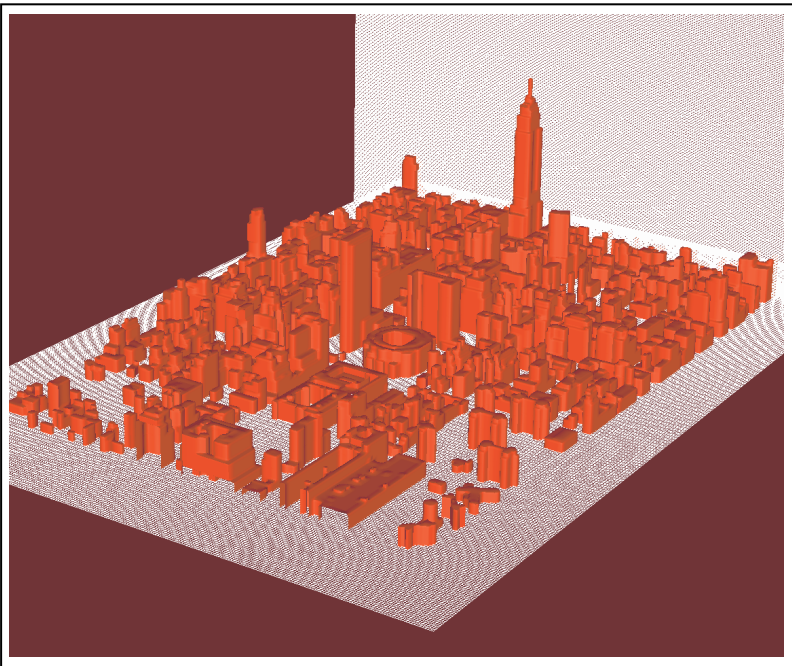

Manhattan meshes
Rapsodi/SAMRAI

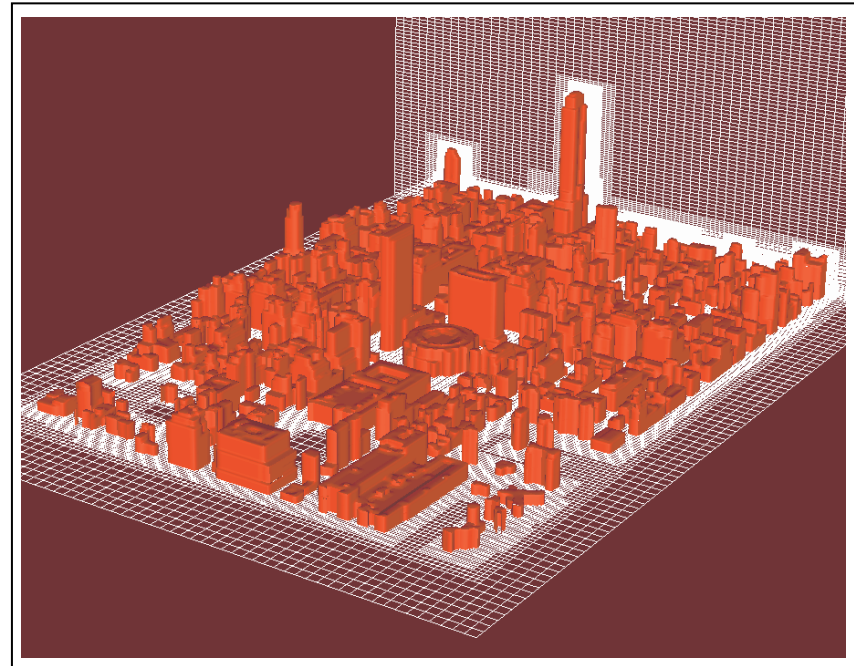**CFD Calculation (non-adaptive)**
FEM3MP

Grid adaptivity will significantly reduce flow solution time

Uniform grid (non-adaptive)
33.6 M gridcells
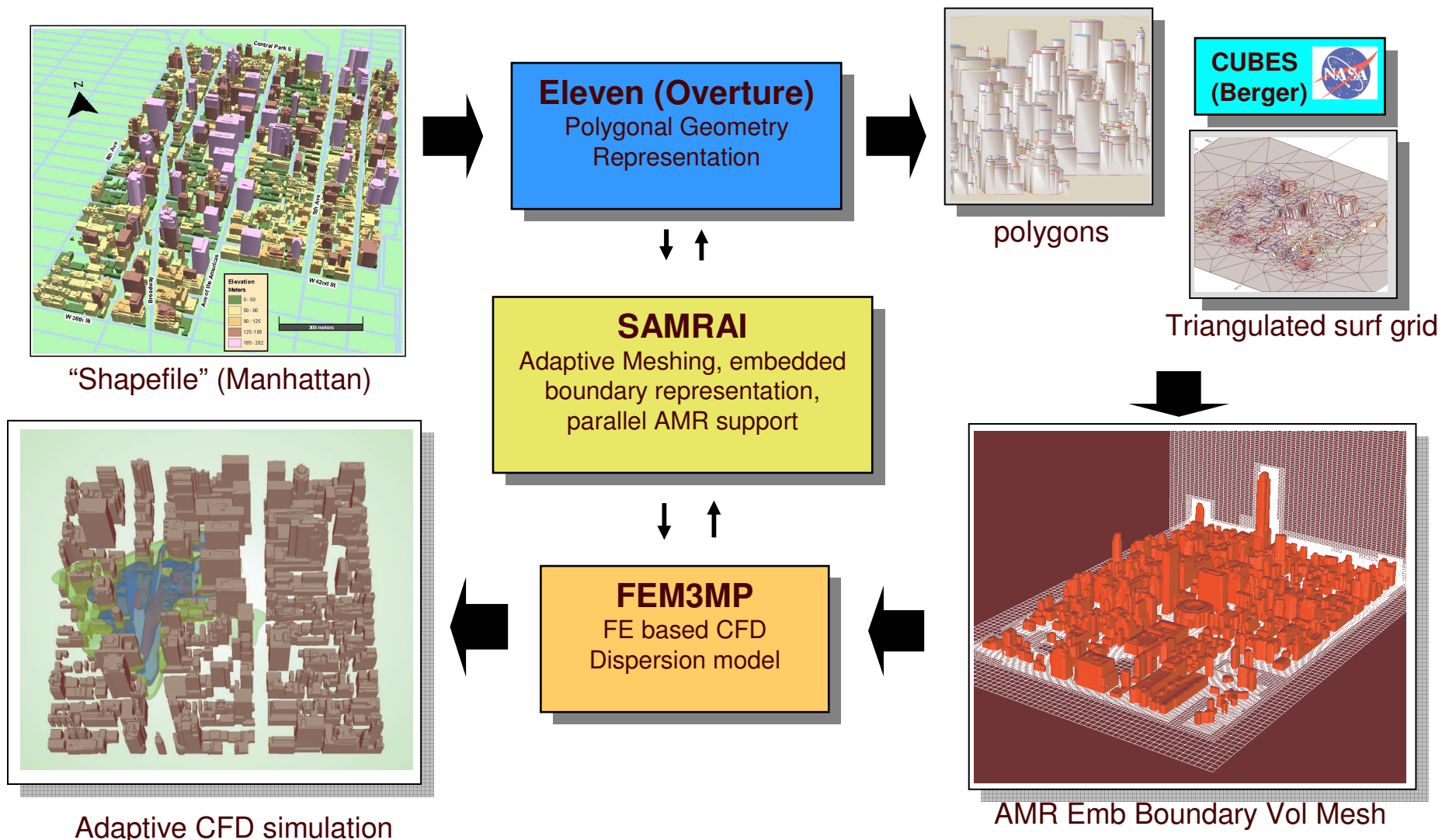
AMR grid
3.4 M gridcells

Lower Manhattan – Madison Sq. Garden/Empire State building
Resolution: 5m horizontal, 2m vertical

Grid generated automatically in < 10 min!

AUDIM applying adaptive meshing for CFD Urban Dispersion Modeling

"Shapefile" (Manhattan)

Eleven (Overture)
Polygonal Geometry Representation

polygons

CUBES (Berger)

Triangulated surf grid

SAMRAI
Adaptive Meshing, embedded boundary representation, parallel AMR support

AMR Emb Boundary Vol Mesh

FEM3MP
FE based CFD Dispersion model

Adaptive CFD simulation

SAMRAI provides interfaces to fast multi-grid solvers in FEM3MP

$$\underbrace{\frac{\partial \mathbf{u}}{\partial t} + \mathbf{u} \cdot \nabla \mathbf{u} + \nabla p}_{\text{advection}} = \underbrace{\nu \nabla^2 \mathbf{u}}_{\text{diffusion}} + \underbrace{\nabla \cdot \overline{u_i' u_j'}}_{\text{turb}}$$ **Momentum**

$$\nabla \cdot \mathbf{u} = 0$$ **Continuity**

$$\frac{\partial c}{\partial t} + \mathbf{u} \cdot \nabla c = \nabla \cdot \overline{c' u_j'}$$ **Scalar advection**

Solution steps

1. Solve momentum equation for **u**
2. **Projection solve** for **p** to apply continuity constraint (linear system solve)
3. Use updated p to **correct u**
4. Scalar advection solve for **c**

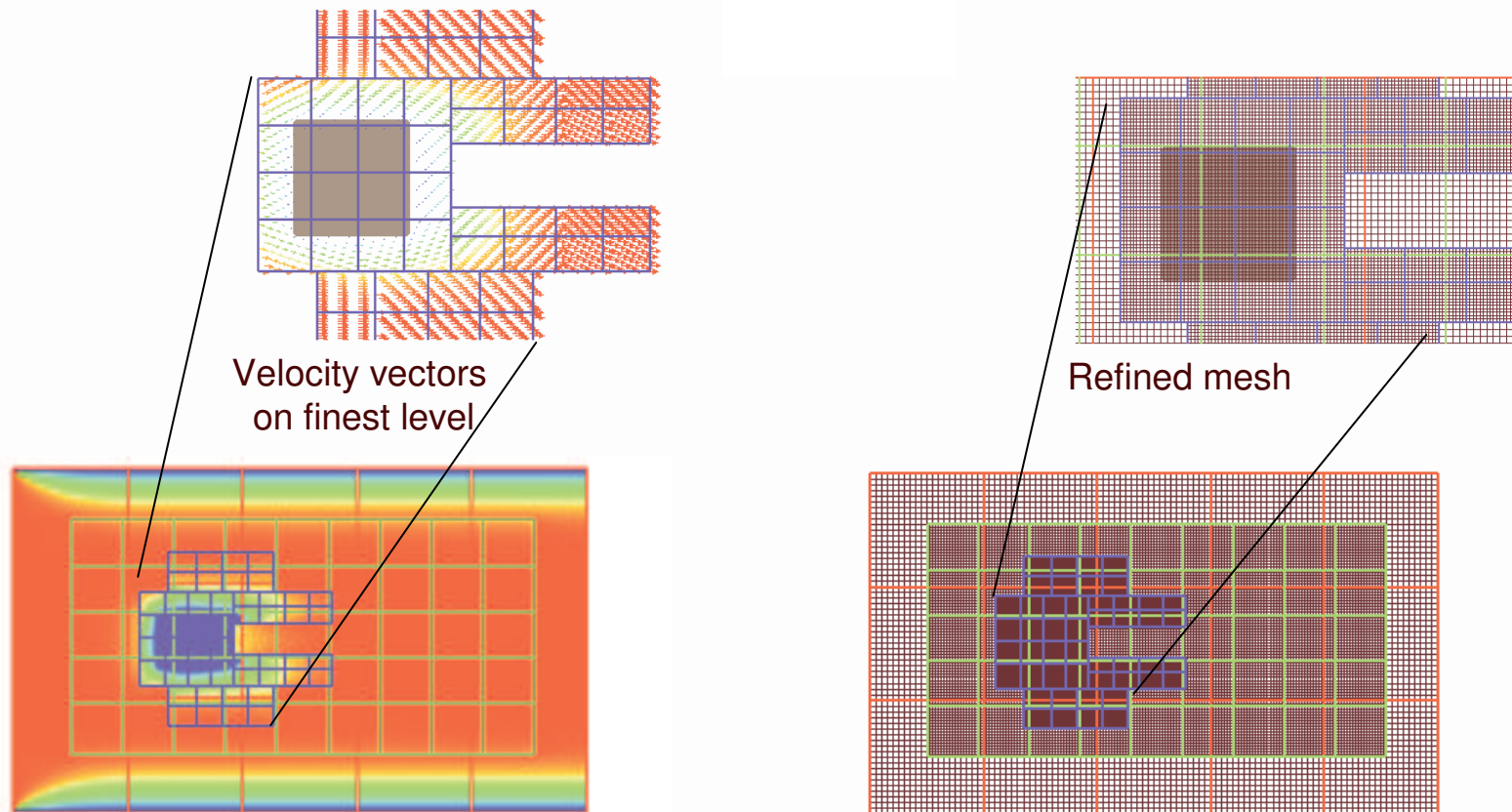SAMRAI's FAC linear solver with links to *hypre's* fast multi-grid solvers

Eliminates "checkerboard" pattern often observed with original code

We are validating preliminary adaptive results

- **3rd Order accurate Runge-Kutta time-stepping scheme**
- **Algorithms for cut-cell representations**

Velocity vectors
on finest level

Refined mesh

2D adaptive solution – pipe flow around square
block with embedded boundary grid

Project tasks and timeline

Started
6/03

1st delivery

2nd delivery

- Demonstration calc with prototypes
- Demonstrate geometry-to-mesh capability
- Develop complex geometry in SAMRAI
- **Deliver gridding tools for NYC**
- SAMRAI-FEM3MP integration
- Develop cut cell FE algs
- Develop AMR capability
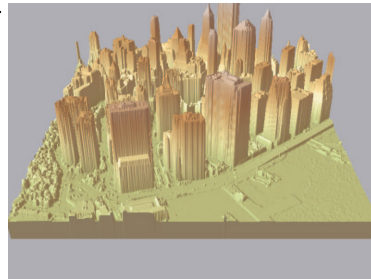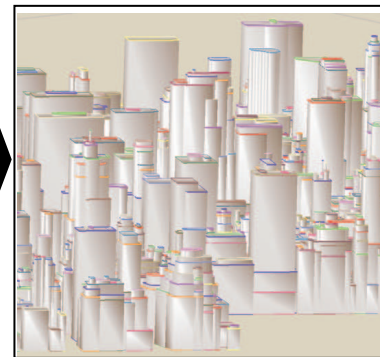- **Deliver adaptive flow solver**
- Fine-tune performance

October
2004

October
2005

2003   2004   2005   2006

FY Timeline
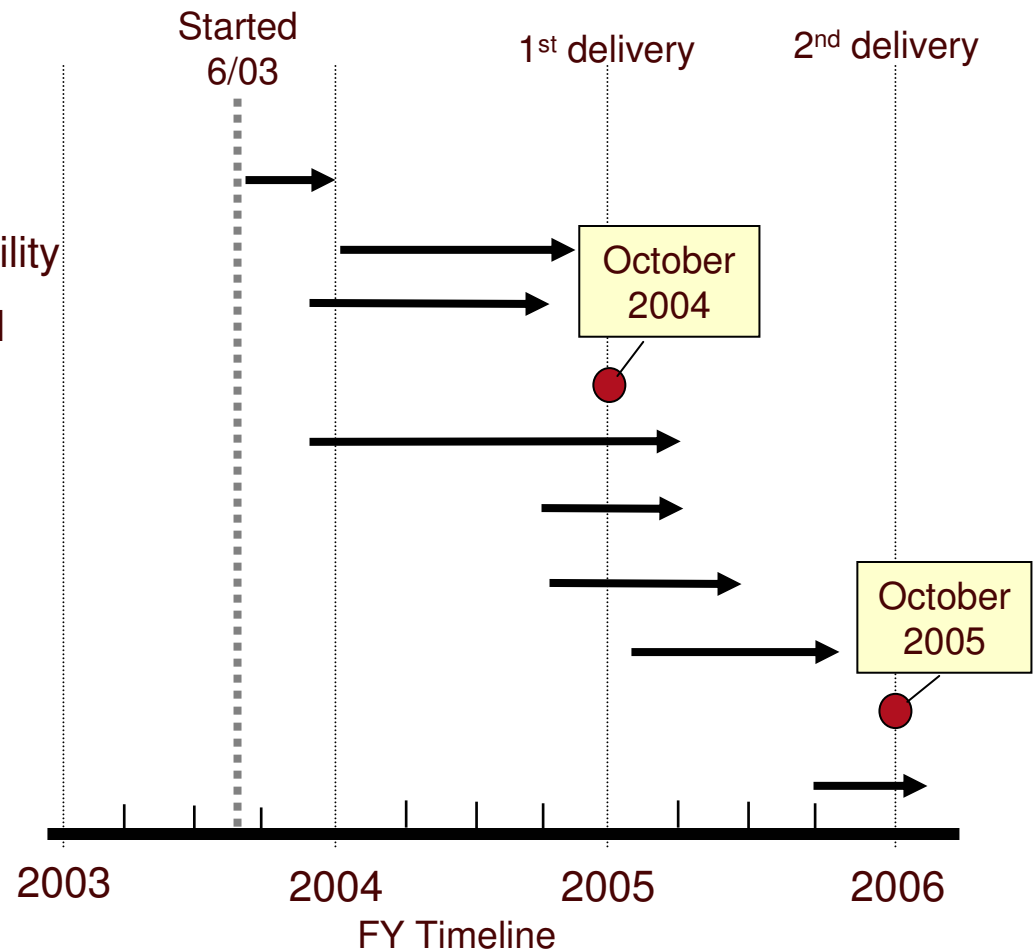
Our long-term vision is a fully automated simulation system
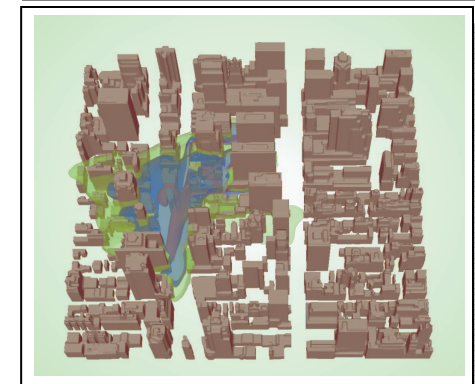

LIDAR - Manhattan

3D Dig. Elev. Map

polygons
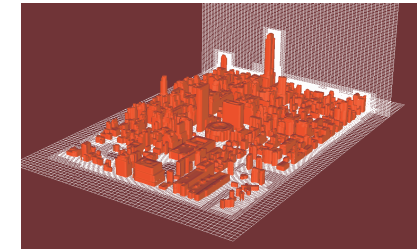
Adaptive Cartesian Grid

Missing Link!

Bluegene/L

Adaptive FEM3MP CFD calculation
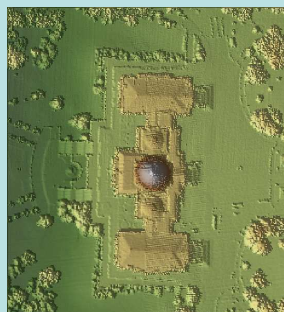
repeat

NARAC Analyst

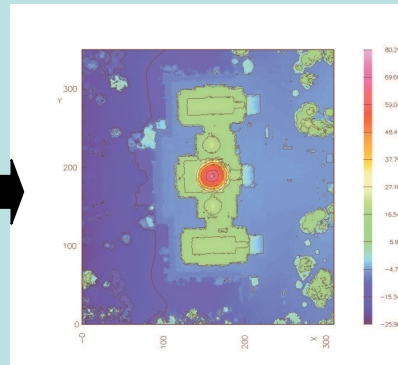# Future: Coupling image processing technologies to simulation

- **Automated airborne LIDAR-to-grid capability**
  - Currently use building shapefile input – limited number of cities available
  - LIDAR data available for almost any US city
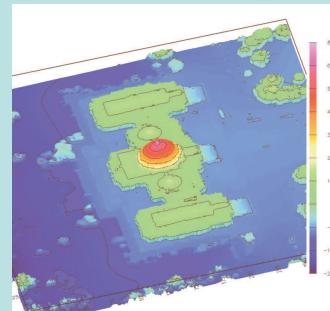 - Automated ways to convert LIDAR to polygonal data
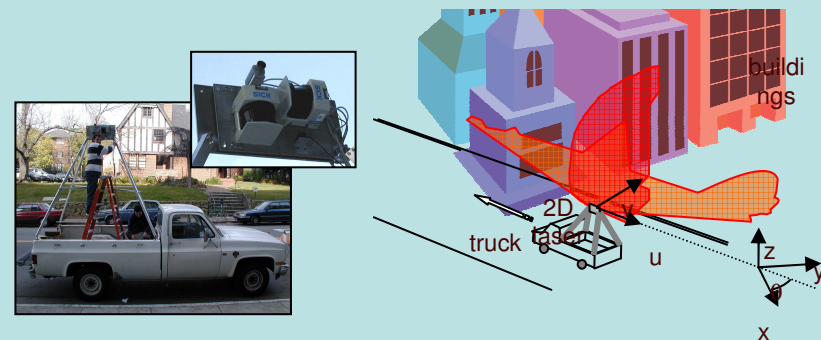
Capitol, Washington DC

LIDAR data

Surface Grid

Polygons for simulation

- **Higher resolution building geometry**
  - Better resolution of building facades
  - Extensions to large indoor spaces

A. Zakhor, UC Berkeley

Concluding Remarks

- **In 2004 we developed advanced gridding tools that are being used by NARAC in support of DHS's Manhattan Urban Dispersion Project (UDP).**

- **In 2005 we are focusing on adaptive solver development**
  - **Fast multi-grid solver added**
  - **Preliminary 2d adaptive results**
  - **Validations with experiment**

- **Pursuing collaborations to develop LIDAR-to-polygons software, the last piece needed for fully automatic LIDAR-to-simulation capability**